Renovation of the lock at Olen – Belgium
Some examples of the use of grouting techniques

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ABSTRACT: The lock at Olen (Belgium) was build in 1938 and has a water level difference of 10 m. The lock showed severe damage caused by erosion of the sandy foundation layers, followed by differential settlements and general cracking of the lock structure. Remedial works were performed using various grouting techniques. As a first measure, the contact between the structure and the foundation layers was restored by means of low pressure grouting under the floor slab and under the lock walls. The stability of the lock walls was ensured by means of vertical tension bars that were anchored in jet grout columns. Further erosion of the foundation soil was prevented by means of a grouted upstream cut-off wall, combined with pressure relief wells under the lock.
Despite the difficult situation for the grouting works in the lock partially in use and the fact that this project was the first to use the technique of the pressure relief wells in a lock structure, measurements of porewater pressure showed that the renovation works were successful. This paper will focus on the difficult situation in which the grouting techniques had to be applied and describes these techniques with their advantages and disadvantages.

1 GENERAL DESCRIPTION OF THE PROJECT

1.1 Situation

The Albert Canal in the Northeast of Belgium, connecting the riverMaas with the harbour of Antwerp, was constructed between 1930 and 1939. Several locks with a water level difference of 10 m each had to be build. Each of these locks consisted of three side-by-side locks: two large locks with length 136 m and width 16 m and a smaller lock of 55 m and width 7.5 m. A sketch of the cross-section is given as Figure 1.

Very soon after the locks were in use several problems arose, as described byKestens et al (1973).

Two of the most important problems were:

- the cut-off screens were to small and totally inefficient
- the three parallel locks were founded by means of one large jointless foundation raft.

These problems caused erosion of the sandy foundation soil and, due to the differential loading, cracking of the whole structure.

In the seventies the capacity of the lock was insufficient and it was decided to demolish the small lock and to build new large locks with a length of 200 m and a with of 24 m for push towing. These locks were constructed taking into consideration all the negative effects learned from the older ones. Up to date these large locks function without important problems.

Because of the intensive use of the Albert Canal, the locks of 136 m are still used continuously. From soon after the problems became clear, one tried to counteract the problems by means of driving cut-off walls around the whole complex and by means of injecting mortar under the floor slab of the construction in order to fill the erosion holes.

A few years ago the situation of the middle lock of the complex atOlen became worse and the stability of the lock walls was questioned. It was decided to execute remediation works in order to stabilise the walls and to prevent further erosion of the foundation layers.

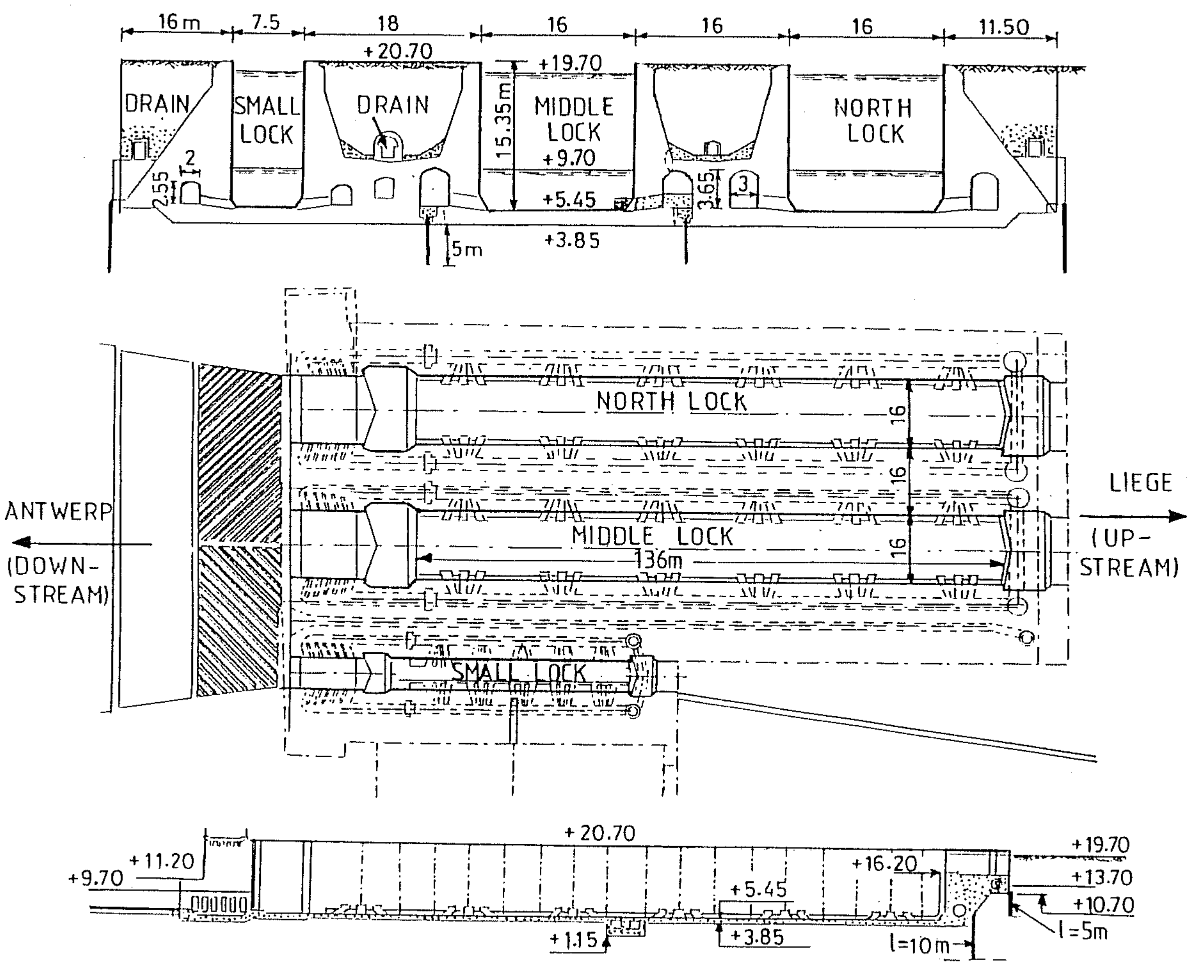

Figure 1. Cross section, plan view and longitudinal section of the locks

1.2 Description of the problems and solution

The lock to be renovated showed following problems:

- fissuring and cracking of the concrete structure
- loss of foundation soil due to erosion; important amounts of sediments were found in the chamber and when the lock was completely emptied in order to execute the renovation works water and soil flowed through the cracks into the chamber. Infiltrating water had to be pumped out of the chamber with a rate of about 100 m^3/h
- differential settlements of the structure; measured on the floor slab: up to 170 mm and measured on the top of the lock wall: up to 130 mm
- tilting of the lock walls and movement of parts of the walls to the inside of the lock
- tilting of the structure as a whole

The cause of these problems was the combination of large cracks, initiated because of the poor design, and the high water pressures underneath the structure. Under the upstream half of the middle lock the head level was as high as +11.5 (referred to datum). The lowerwaterlevel in the lock is only +9.7 and the slab has a thickness of 1.6 m. This means that, due to the head difference of 1.8 m, the gradient of the waterflow through the cracks in the slab is lager than the critical gradient. When the cracks are large enough, the groundwater flow through the cracks causes transport of the foundation sand. This loss of bearing caused settlements, enlarging the fissures and cracks.

This vicious circle could not be stopped with the injection of a mortar under the floor slab as was done with a few years of time interval. Each time again large amounts of mortar could be injected under the floor slab.

Permanent measures were needed so as to prevent further erosion and, even more important, stabilise the lock walls.

As it was considered impossible to repair the lock chamber so as to achieve a watertight structure the waterpressures under the floor slab had to be lowered. This was done by means of porewater pressure relief wells combined with an upstream cut-off wall which is effective. The general groundwater flow around the locks and theporewater pressure relief wells was described by Maertens et al (1999).

Apart from the prevention of erosion, also the stability of the lock walls had to be secured. This was done by means of founding and prestressing the walls.

To be able to perform these works various grouting techniques were needed:

- To restore the bearing capacity of the foundation raft an before qualitative grouting could be done, the erosion holes under the floor slab and the walls had to be filled. This was done by means of low pressure grouting with a special grout mixture.
- The lock walls were stabilised by means of vertical tension bars anchored in jet grout columns under the walls; these grout columns have a double function: foundation piles and anchorage of the tension elements.
- Through the upstream head of the lock, holes were drilled and a row of intersecting jet grout columns was made to realise the cut-off wall.

2 SOIL CONDITIONS

Soil investigation consisted of CPT(U)-tests, borings with sampling and installation of standpipes. In situ tests were performed around the structure and underneath the structure.

A typical result of a CPT test and a sieving curve of the foundation sand is given in Figure 2 (full line) and Figure 3. The CPT test shows that the original undisturbed foundation layers consist mainly of well compacted sand with a total thickness of over 15 m and with cone resistance between 20 MPa and 35 MPa.

In the zone immediately under the floor slab sometimes holes or very loose sand was found, although this was not a systematic evidence. This is typical for an erosion problem that causes flow pipes which continuously enlarge.

Under the upstream head of the lock a more important layer of loose sand or disturbed sand was found as shown by the CPT result given in Figure 2 (dotted line). This layer has a thickness of about 6 m and could be the result of poor compaction during construction or of the important groundwater flow around this part of the structure.

To define the hydraulic permeability a pumping test and laboratory permeability tests were performed. The hydraulic permeability of the foundation sand deduced from the tests is $k_h = 2.10^{-4}$ m/s; $k_v = 2.10^{-5}$ m/s.

A grid of standpipes (piezometers) was installed to monitor thegroundwaterflow before, during and after the renovation works. This monitoring was necessary to be able to model the effect of the porewater pressure relief wells and the cut-off screen and to evaluate the final result of the measures taken after completion.

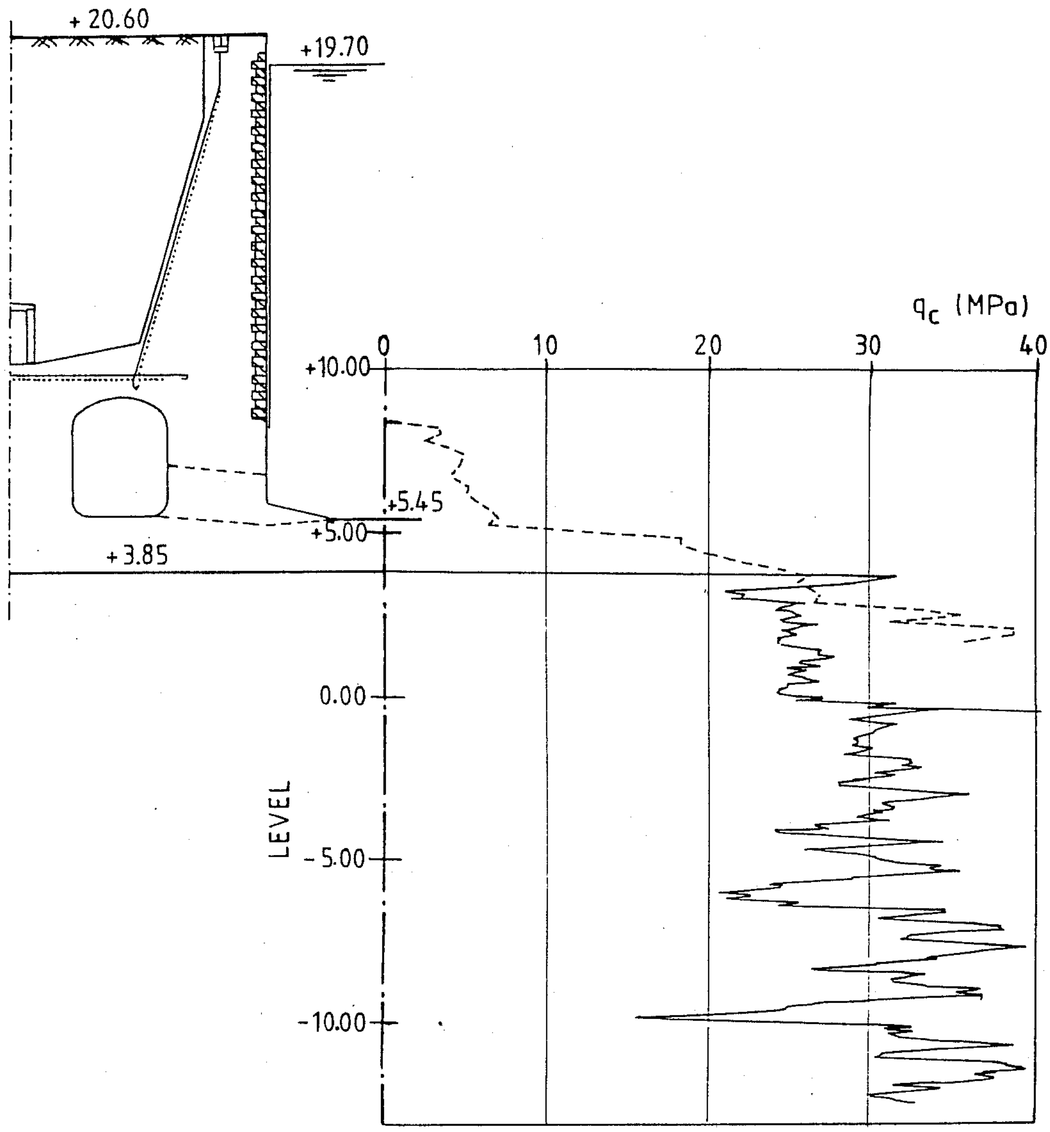

Figure 2. Typical CPT results. Full line: under the lock chamber; dotted line: under the upstream head of the lock.

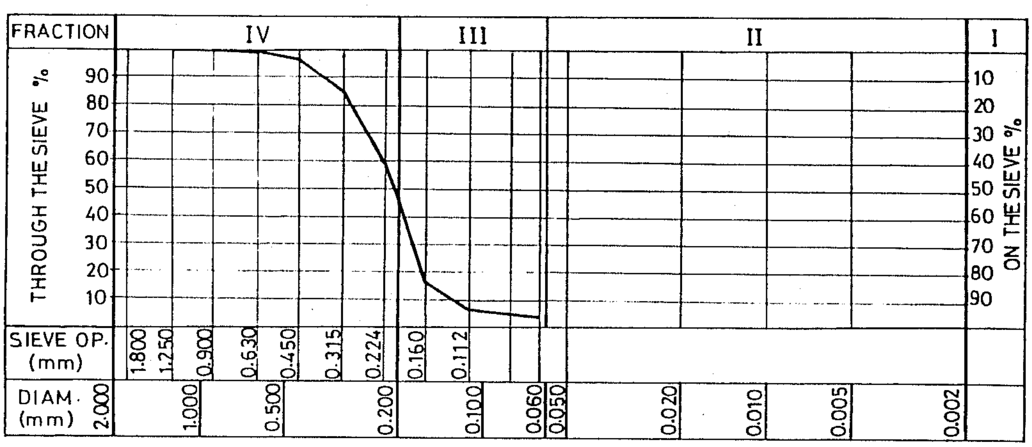

Figure 3. Typical sieving test result

3 STABILISATION THE FLOOR SLAB BY MEANS OF LOW PRESSURE GROUTING

During the execution of these works the lock was dry, causing an even more heavy groundwater flow underneath the lock. Injections under the floor slab of the lock were performed through a grid of injection points with a spacing of 4 m. Because of the waterpressure under the slab, special measures had to be taken during boring through the slab and during injection.

Pumping was performed with a pressure of 275 kPa. The pumping was continued until grout was detected at one of the neighbouring injection holes. Grout volumes up to several m^3 were injected in some points; at one spot, a volume of 20 m^3 was injected, but part of the injected grout was pumped into the canal.

Because of the groundwater flow, the grout mixture was especially studied in order to prevent washing out of the cement and to ensure rapid hardening without shrinkage. Some characteristics of this material are: Water/Cement rate 0.8; Viscosity (March time) 4 s; density 1.58; bleeding and shrinkage < 2.8%.

Quality control of these injection works consisted of checking the grout mixture (density, compression strength, ...) with regular intervals and measuring the injected volumes. After the injection works, it was clear from the reduced amount of water to be pumped out of the chamber that the injection works were successful. Also when later borings through the slab were performed often a layer of injected material was found underneath the concrete of the slab.

Only the injections under the upstream head of the lock were less successful. This was attributed to the fact that the bottom of the concrete structure at this place is inclined (Figure 4) and to the fact that possibly direct hydraulic connections existed with the upstream part of the canal.

4 STABILISATION OF THE LOCK WALLS BY MEANS OF ANCHORING

Figure 5 shows a cross section of the lock walls. Horizontal cracking could be seen at various levels from the top of the floor slab up to the head of the wall. Sometimes whole parts of the wall had moved towards the lock as one block. Movements up to some cm were measured.

To ensure a reliable foundation 3 rows of jet grout columns were executed underneath the walls through inclined borings. The piles reach to a depth of 8 m under the original foundation level, ensuring a bearing of the piles in undisturbed soil and sufficient length for the anchorage of the tension bars.

To restore the homogeneity of the walls, vertical prestressing was performed. The vertical tension bar needed to be achored under the lowest horizontal crack in the structure, being the top level of the slab. As the thickness of 1.6 m of the slab was not enough for the anchorage of the tension bar, the jet grout columns were used to anchor the tension elements. In this way some of the jet grout column rows got a double function.

As the quality in terms of strength was the most important here and the diameter of the columns needed not to be more than 800 mm, mono-jet grouting was used. As quality control compression tests were performed on the grout mixture before injection, on the 'reflow' of the soil-grout mixture and on core samples taken from the hardened columns. Table 1 gives some representative results of these tests. As a lower limit, a characteristic compression strength f_{ck} = 8 N/mm^2 was set as requirement. This value was reached in the majority of the tests (>95%). The sampling rate for quality control was: 4 samples of the soil/grout mixture and 1 core boring (2 samples)every 15 piles. Tests on the grout mixture were done only in the beginning to check the grout quality.

Table 1. Grout quality achieved by means of mono-jet grouting. Values of compression strength (N/mm²) at 28 days.

Column nr.	Column diam. (m)	Grout mixture	Grout/soil mixture	Core samples
test		13.03 and 12.54		
62	0.8			10.44 and 19.27
62	0.8			15.33 and 21.51
98	0.8		16.82	
70	0.8		23.87	

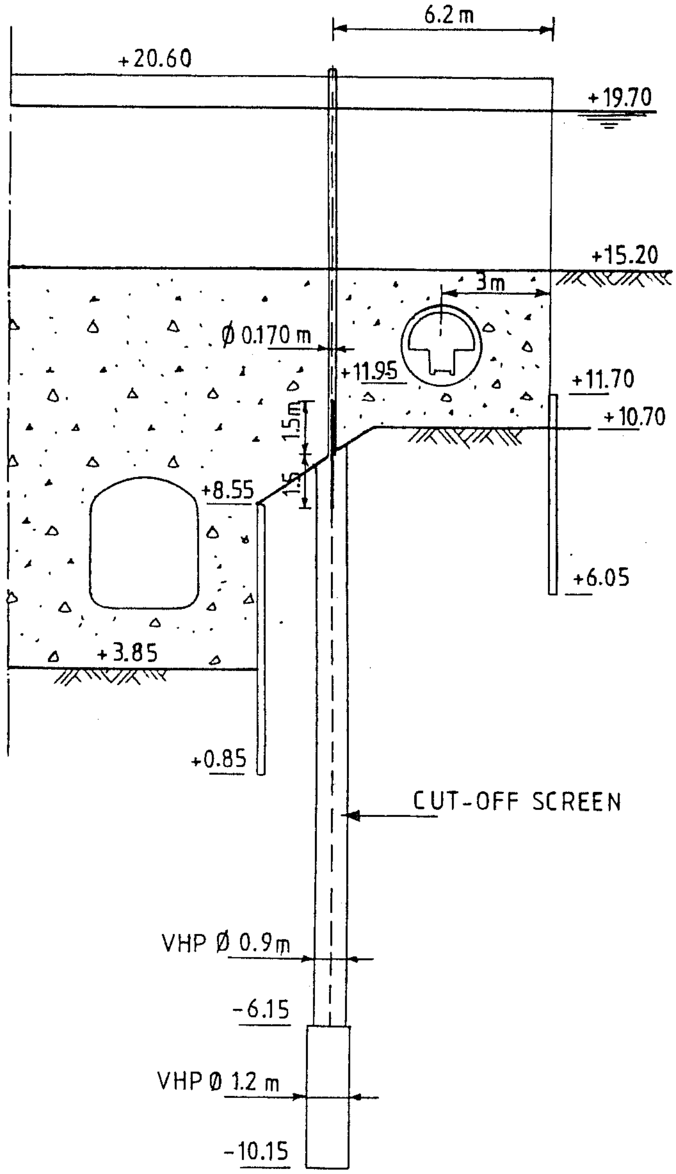

Figure 4. Longitudinal section of the upstream head of the lock

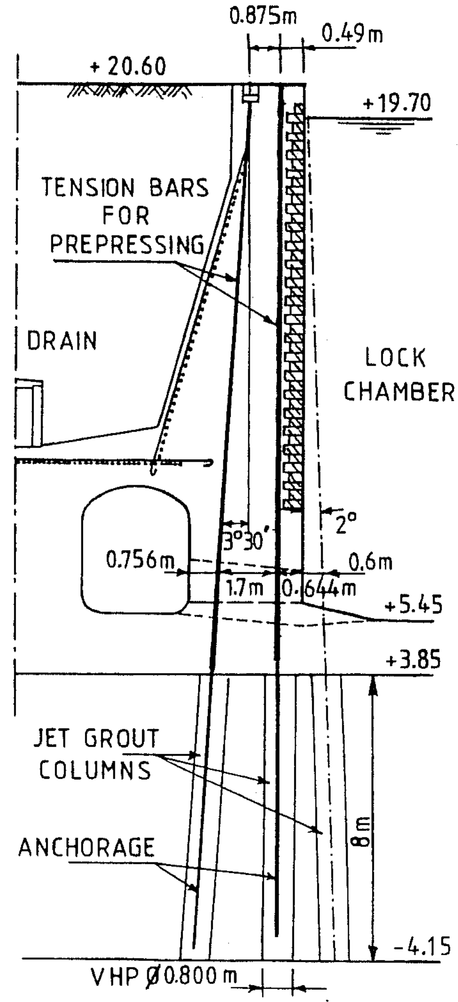

Figure 5. Cross section of the lock wall with jet grout columns

5 CUT-OFF WALL

The cut-off wall up to 14 m under the lowest floor level of the lock structure had to be executed under very difficult conditions. Figure 4 gives the longitudinal cross section of the upstream head of the lock. The position of the cut-off wall is indicated on this section. This position was selected as being the most appropriate. The borings through the concrete structure had to be very precise: verticality and position between conduits etc. The bottom of the concrete structure at this section is inclined, making the work even more difficult.

To avoid to much problems a maximum interdistance of 0.60 m of the grout columns was chosen. Since the watertight cut-off wall had to be performed with a single row of columns, the overlap between the secondary and primary columns had to be guarantied. In order to create a maximum diameter of the jet grout columns, thebi-jet grout technique was chosen. A diameter of 1.20 m is easily possible with this technique.

It was already pointed out that the soil conditions at this part of the construction were not good. Because of the loose compaction of the fine sand over the first 6 m the stability of theborehole could not be guarantied when using bi-jet grouting. Due to the upward stream of air, the walls of the boring might collapse, with as a result poor quality grouting and possible holes in the cut-off screen.

To overcome this problem the first 6 m of the columns were performed with mono-jet grouting. At these depths the error caused by the eventually inclined borings were still limited and a diameter of the columns of 0.90 m was sufficient. These columns were made first. After a few days of hardening the bi-jet piles with a total length of 14 m were made through these mono-jet piles, underneath them.

The position of each of the jet grout columns was measured before the jet grouting started. By means of inclinometer measurements the inclination of the borings through the concrete structure was measured. After extrapolation, the position of the grout columns with diameter 0.90 m and 1.2 m could be estimated and plotted on a drawing of the situation. When the overlap between the columns was not enough, two actions were possible:

- making larger diameter columns through the adaptation of the grouting parameters; diameters up to 1.4 m were possible, tough with a high cement consumption and with a low production rate;
- making an extra column to close the opening between columns.

The grouting was done by means of side by side grouting of the columns, not with primary and secondary grouting. Out of experience on other comparable jobs it was believed that in this way a more homogeneous thickness of the cut-off wall is achieved. This however could not be proved.

The grout quality was measured in the same way as described above. As an extra parameter, the hydraulic permeability of the soil-grout mixture was tested. Out ofthe theoretic modelling of the groundwater flow, a maximum value of $1\ 10^{-7}$ m/s was set as requirement. In table 2 some results of tests on the grout are given.

The compression strength was less important here and, due to the bi-jet grout, the value $f_{ck} = 8$ N/mm^2 could not be guarantied. About 12 % of the tested samples showed lower values.

Table 2. Grout quality achieved by means of bi-jet grouting (at 28 days).

Column nr.	Column diam. (m)	Grout/soil mixture f_{ck} (N/mm²)	Core samples f_{ck} (N/mm²)	Core samples k (m/s)
75	1.2	14.86 and 12.53	5.15 and 5.9	$3.3\ 10^{-7}$
116	1.2	6.82 and 8.13	22.14* and 26.02*	$4.5\ 10^{-10}$ and $4.3\ 10^{-11}$
126	1.2	5.79 and 6.37	12.46 and 21.76	$1.3\ 10^{-7}$ and $5.26\ 10^{-11}$
135	1.2	18.01 and 18.39	16.39* and 26.96*	$3.57\ 10^{-7}$ and $1.28\ 10^{-10}$
40	1.2	13.77 and 14.33	32.06 and 29.67	

* *at 72 days in stead of 28 days.*

6 IMPORTANCE OF QUALITY CONTROL

The quality control that was performed for each of the techniques is described above. Since with the technique of grouting and jet grouting the result can only be checked by means of destructive and expensive testing, the monitoring of execution parameters is of utmost importance.

Before the grouting in the field started, some test piles were performed in comparable soil conditions in the direct neighbourhood of the works. From these tests, grouting parameters and grout quality after injection and mixing with the soil was defined. During execution of the piles the grouting parameters were continuously checked.

These parameters were:

- Cement quantity of the grout material
- Boring liquid for boring downward: water or cement mixture,
- Technique used: mono or bi-jet
- Number of nozzles and diameter
- Grouting pressure and air pressure
- Rising speed and rotation speed of the jet grouting
- Volumes of grout material used

Also the diameters of the test columns were defined. When coring for quality control after execution and hardening of the piles, the diameter was approximately checked by means of borings performed at the edge of the grout pile.

To guaranty the water tightness of the cut-off screen, especially because the screen was executed with a single row of jet grout columns, the overlap of the columns needed to be checked. This was done as described above by means of the measurement of the inclination of the borings through the concrete of the structure. At some spots, were it was possible, an extra boring with coring was performed in the overlap between columns. As a first control, evidence of the presence of grout material was achieved and, when no problems were detected, the quality of the material was tested. It should be mentioned that for this type of quality control, the verticality and the quality of the core boring itself is of great impact.

7 FINAL MEASUREMENTS AFTER CONSTRUCTION

After completion of the renovation works, theporewater pressures and the discharge of the relief wells are measured continuously, using the grid of standpipes installed from before the works started. It can be seen from these measurements that thewaterpressure under the floor slab are lowered to a level so as to prevent transport of sand through the cracks in the slab.

The waterpressures measured and the discharge are in good agreement with the theoretical predictions, proving that the renovation of this lock was successful.

8 CONCLUSIONS

The renovation of a lock, being part of a whole complex which has to remain in use during the renovation works, was a complex situation. Very few alternatives were available for the execution of these works, apart from totally rebuilding the lock. Various grouting techniques were used for quite different applications in one project. This shows the very powerful nature of this foundation engineering technique.

A permanent solution could be given to a problem that was going on for several decades now. Measurements after completion of the works prove that the renovation works were successful.

Since visual checking of the results after construction is impossible, quality control and adequate monitoring during execution is needed. In the paper it is pointed out how this can be performed.

9 REFERENCES

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